TELESCOPE SCIENTIST ON THE ADVANCED X-RAY ASTROPHYSICS OBSERVATORY

NASA Grant NAG8-1607

Annual Report

For the Periods 1 October 2000 through 30 September 2001

Principal Investigator
Dr. L. Van Speybroeck

January 2002

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Carl M. Smith, Code FD03, NASA, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812.

Semiannual and Annual Reports
NASA Grant NAG8-1607
AXAF Telescope Scientist
Period of Performance: 1 October 2000 through 31 December 2001

1. Introduction.

This period included many scientific observations made with the Chandra Observatory. The results, as is well known, are spectacular. Fortunately, the HRMA performance continues to be essentially identical to that predicted from ground calibration data. The Telescope Scientist Team has improved the mirror model to provide a more accurate description to the Chandra observers and enable them to reduce the systematic errors and uncertainties in their data reduction.

There also has been progress in the scientific program. At this time 47 distant clusters of galaxies have been observed. We are performing a systematic analysis of this rather large data set for the purpose of determining absolute distances utilizing the Sunyaev Zel'dovich effect.

2. Chandra Mirror Calibration.

2.1. Effective Area

We continued the study of the HRMA absolute effective area (EA), which is one of the most important parameters of the Chandra X-ray Observatory. Last year, we derived the HRMA EA curve using the Solid State Detector (SSD) C-continuum data obtained during the HRMA calibration at the XRCF that agrees with the ray trace prediction within 1% on most of the energies. However, there is an experimental discrepancy of 2%–5% between the FPC spectral line data and the SSD C-continuum data. We re-examined the discrepancies between the SSD and FPC data; reran all the ray traces using the new optical constants and the scattering table; generated polynomials that fit the ratio of the ray trace and the SSD C-continuum data, then scaled the results using 50% of the average difference between the FPC data and the SSD data. Finally we used this scaling function to calibrate the ray trace results to generate the HRMA effective area models. We presented these new HRMA effective area results at various meetings and posted them on the CXC calibration web page. The new "HRMA On-orbit On-axis Effective Area" tables have been implemented in the Chandra Calibration Database with the release of CIAO (Chandra Interactive Analysis of Observations). They also have been included in the "Chandra Proposers' Observatory Guide", and distributed to the Chandra community for making the on-orbit performance predictions and for other Chandra teams to calibrate their science instruments.

In the process of making the new HRMA effective area tables, we re-examined all the synchrotron optical constants data, made global fits to the optical constants curves to remove local glitches and to make smooth joints between Gullikson and synchrotron data. The results are the smooth optical constants tables currently used in the ray trace programs.

We performed ray trace calculations of the HRMA on-orbit encircled energy for both on- and off-axis cases, and built a library of the PSF for on and off-axis (up to 20 arc min off-axis and in 8 azimuthal directions) for HRMA, HRMA/HRC-I, HRMA/HRC-S, HRMA/ACIS-I, and HRMA/ACIS-S, with and without the telescope aspect errors.

2.2. Scattering and Off-Axis Performance

We continued the study of X-ray scattering from random rough surfaces. The goal of this study is to establish an accurate scattering model for the Chandra and future X-ray telescopes. We have written a program to construct a random rough surface for any given PSD. Many random rough surfaces can also be constructed from the same PSD profile by varying the phase factors for each frequency (phase factors are set by a random number generator as the PSD data do not include this information). This work is still in progress. The next step is to do the diffraction integrals using the constructed rough surface.

2.3. On-Orbit HRMA Calibration

We refined our estimates of the HRMA on-orbit focal length, which is important as the focal length is directly proportional to the Chandra focal plane plate scale. The designed HRMA on-orbit focal length (for an ideal HRMA) is 10065.54532 mm. For the real HRMA, there was no direct measurement of its on-orbit focal length possible before launch. However, there were six different estimates of the absolute distance between the HRMA on-orbit focus to the front surface (paraboloid side) of the Central Aperture Plate (CAP Datum A), based on several independent direct measurements during various stages of the Chandra development at Kodak and TRW. We used these values and did a ray trace study based on a method we designed to calculate the HRMA On-orbit focal length, which turns out to be 10069.8$\pm$1.1mm (90%). We posted a memo of this result on the CXC calibration web page and it later agreed very well with the averaged on-orbit measurements (from both HRC and ACIS) of 10070$\pm$3mm (90%). This value is now adopted as the HRMA on-orbit focal length.

3. The Funtools Project

The Funtools project arose out of conversations with astronomers about the decline in their software development efforts over the past decade. A stated reason for this decline is that it takes too much effort to master one of the existing FITS libraries simply in order to write a few analysis programs. This problem is exacerbated by the fact that astronomers typically develop new programs only occasionally, and the long interval between coding efforts often necessitates re-learning the FITS interfaces.

We therefore set ourselves the goal of developing a minimal buy-in FITS library for researchers who are occasional (but serious) coders. In this case, "minimal buy-in" meant "easy to learn, easy to use, and easy to re-learn next month". Based on conversations with astronomers interested in writing code, we concluded that this goal could be achieved by emphasizing two essential capabilities. The first was the ability to write FITS programs without knowing much about FITS, *i.e.*, without having to deal with the arcane rules for generating a properly formatted FITS file. The second was to support the use of already-familiar C/Unix facilities, especially C structs and Unix stdio. Taken together, these two capabilities would allow researchers to leverage their existing programming expertise while minimizing the need to learn new and complex coding rules.

3.1. Design Approach

Our design approach was to *minimize the number of public subroutines* in the Funtools library. This approach was based on the hypothesis that a few carefully crafted routines would be easy to learn, easy to remember, and easy to use by occasional coders. In other words, we sought to make it easier to "see the forest for the trees" by minimizing the number of trees.

The implications of this approach were two-fold. Firstly, the routines would have to be useful in their basic operation, while containing appropriate hooks to activate more sophisticated functionality. That is, we tried to avoid automatically adding routines to the library in order to extend functionality. Instead we sought to accomplish this aim by adding optional keyword specifiers to the calling sequence of our basic routines, taking care to avoid making those routines overly complex along the way.

Secondly, we decided that routines should act on behalf of the coder, especially with regard to FITS formatting issues (*e.g.*, header generation and extension padding). We recognized that proper formatting of FITS files is one of the most difficult and tedious parts of FITS programming, and we wanted Funtools to provide this service automatically. For example, when image or binary table data is written, the associated headers should be generated automatically as needed. In doing so, great care must be taken to ensure that all necessary parameters (including user-specified parameters) are correctly incorporated into the header. Designing such automatic services required that we maintain the "state" of processing for a given FITS file, so that the library could "do the right thing" on behalf of the user.

3.2. Implementation

Our implementation strategy was centered on perfecting the code needed by a select few image and table processing algorithms, including the canonical X-ray analysis task: for each X-ray event (row in a binary table), read selected input columns into user space, modify the value of one or more of these columns, and output the results by merging new value(s) with the original input columns. The Funtools library implements this standard X-ray event-processing algorithm in a simple and straightforward manner.

In Funtools, much of the complexity of dealing with FITS is hidden. FITS headers and extension padding are written automatically as needed. Output files easily inherit input parameters and other extension information. Copy of input extensions is specified easily on the command line. The price paid for these automatic services is the imposition of some rules of "natural order" (for example, not closing an input file before its contents are used to generate an output file), although options are available for cases where coders are forced to violate these rules.

3.3. Advanced Filtering Capabilities

As part of the Funtools library, events in FITS Binary tables and raw event files can be filtered or selected based on a flexible set of user-specified criteria that allows column values to be compared with numeric values, header parameters, functions, or other column values.

In addition to filtering columns of binary tables, our funtools library also can filter both events and images using spatial regions specifiers. Spatial region filtering for images and events is accomplished by means of region specifications. A region specification consists of one or more region expressions, which are geometric shapes,combined according to the rules of boolean algebra. When an image is filtered, only pixels found within these shapes are processed. When an event list is filtered, only events found within these shapes are processed.

To implement event and spatial region filtering, funtools utilizes a technique in which the filter specification is converted into a small C program, which is compiled and linked automatically so that events or image sections can be fed to this program and filter results returned to the calling program. The power of the technique lies in these considerations:

- The generated filter program is very small, containing approximately 200 lines of code, so that it compiles and links in about second or less on most modern machines.
- The filter specification itself becomes a hard-wired part of this program, so that filter checking is performed as part of compiled code, not in the usual interpreted mode. This use of a compiled filter results in a speed-up factor of 4-5 over previous techniques, even after the program compilation time is added.
- All C syntax and C operators become valid parts of the filter syntax, making available a much wider range of filter possibilities than previously.

3.4. Dissemination

Funtools is available in beta release at http://hea-www.harvard.edu/RD/funtools. The library has been ported to Sun/Solaris, Linux, Dec Alpha, SGI, and Windows (using Cygwin). We also offer a number of sample programs such as funcnts, which calculates the background-subtracted image counts in user-specified regions. A paper discussing Funtools entitled "Funtools: an Experiment in Minimal Buy-in Software" (E. Mandel, S.S. Murray, J. Roll) was presented at the ADASS200 conference.

4. Miscellaneous Program Support.

The Telescope Scientist Team provided support on a number of technical problems which were encountered during this phase of the program, including contributions to the understanding of the ACIS charge transfer inefficiency problem. We also worked on the release of NASA's Chandra AO3 and AO4 Research Announcements. We rewrote and updated the HRMA chapter of the "Chandra Proposers' Observatory Guide", which was sent to all the Chandra proposers with the NASA's Chandra AOs.

5. Science Program.

The Telescope Scientist guaranteed time is devoted to observations of distant galaxy clusters to study their evolution and to determine cosmological scale quantities using the Sunyaev Zel'dovich effect. Cooperative agreements with other scientists, including radio observers, have been formed. Preliminary data processing has been performed upon the 47 data sets received at this time. This processing includes correction for the changes in the ACIS gain, the identification and elimination of periods of high background, the removal of ACIS after-glow effects, the calculation of exposure maps and images, and the search for serendipitous sources. The superior angular resolution of Chandra shows more structure in galaxy cluster systems than we had expected based upon pre-Chandra observations; this significantly complicates the final data analysis.

The selection of the data to be analyzed as part of the cluster emission and also the regions selected for background evaluation must be done systematically; code has been developed for this purpose. A typical example is shown in figure 1. The data field first is divided into local cells by a tessellation routine; each such cell consists of the area which is closer to a particular detected photon than any other. High surface brightness areas are characterized by small tessellation cells. Individual sources are identified as contiguous small cell regions. The irregular contours in figure 1 outline the sources detected by this technique; areas outside of these contours are used for background estimation. The source regions identified by this technique then are processed to determine the source convex hulls; these are shown as irregular polygons surrounding the tessellation source contours in figure 1. Finally, the smallest area ellipse which includes the convex hull is determined; this ellipse is used as the starting point for source analysis and model fitting.

Dr. Ping Zhao continued his study of stellar black holes. This includes the search for new black holes and the study of known black holes. Dr. Zhao is the principal investigator of a program to monitor the quiescent black hole X-ray novae (BHXN). It was believed that X-ray Novae are extraordinarily dormant in their quiescent state. However, this monitoring program has revealed unexpected optical and X-ray activities of quiescent BHXN. Because the optical variability is most likely due to variations in the accretion flow in the disk, this study provides a unique opportunity to test the reality of ADAF-based model for BH event horizons. This program also monitors the light curve of newly discovered X-ray novae and prompts timely observations of their radial velocities once they entered the quiescent phase, in order to determine the mass of their primaries. Dr. Zhao also is the principal investigator of a program to search for quiescent X-ray novae among the old optical novae. The goal of this study is to discover new black hole candidates and thereby to increase our knowledge of galactic black hole population and evolution.

We also continued to participate in the Chandra Multiwavelength Plane Survey Project (ChaMPlane) which is a project to identify a large sample of serendipitous X-ray sources in the galactic plane Chandra fields, in order to determine the populations of accretion-powered binaries in the Galaxy. The primary goal is to identify cataclysmic variables (CVs) and quiescent low-mass X-ray binaries (qLMXBs) in order to constrain and ultimately measure their number and space density. The qLMXB sources may contain either a neutron star or a black hole; the latter is more common among the known sources. The secondary goal is to determine the Be X-ray binary (BeHMXB) content and stellar coronal source distributions in the Galaxy. Deep Chandra field observations have sufficient sensitivity to reach a substantial fraction of the galactic disk. This study is important because the total number of CVs in the Galaxy remains highly uncertain, with estimates varying by a factor of 100. This is largely a result of the fact that most known CVs have been discovered optically, typically within a distance of only 1 kpc. The much larger limiting detection distance of the ChaMPlane Survey should substantially increase the number of CVs detected in the Galaxy. This work will greatly increase our knowledge of the evolution of stars.

We presented three papers at the AAS meetings as first authors, and also were co-authors of a number of other astrophysical publications (IAUC and ApJ).

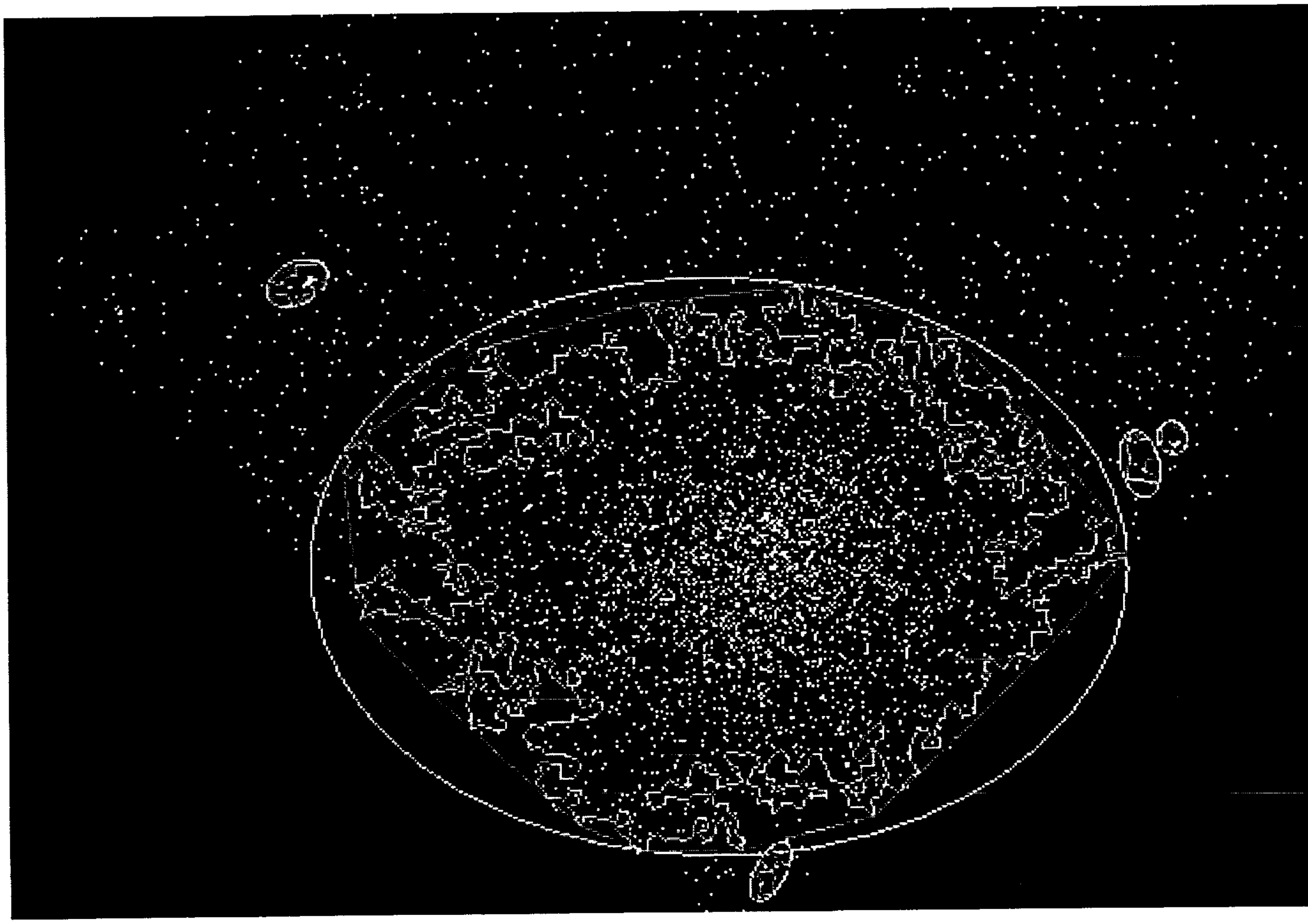

Figure 1: This is a typical example of a cluster image. The irregular contours are source regions identified by a tessellation routine; the field outside of these regions is used to estimate the local background. The polygons surrounding the irregular contours are the convex hulls of the regions identified by the tessellation routine. The smooth curves are the minimum area ellipses which include the convex hulls; these ellipses define the initial regions used for data analysis.